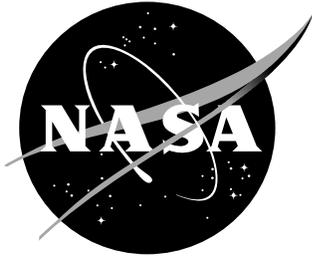


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# Validation of Force Limited Vibration Testing at NASA Langley Research Center

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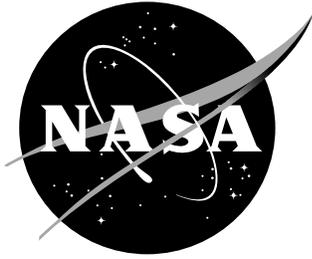
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# Validation of Force Limited Vibration Testing at NASA Langley Research Center

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## Abstract

Vibration tests were performed to develop and validate the forced limited vibration testing capability at the NASA Langley Research Center. The force limited vibration test technique has been utilized at the Jet Propulsion Laboratory and other NASA centers to provide more realistic vibration test environments for aerospace flight hardware. In standard random vibration tests, the payload is mounted to a rigid fixture and the interface acceleration is controlled to a specified level based on a conservative estimate of the expected flight environment. In force limited vibration tests, both the acceleration and force are controlled at the mounting interface to compensate for differences between the flexible flight mounting and rigid test fixture. This minimizes the over test at the payload natural frequencies and results in more realistic forces being transmitted at the mounting interface. Force and acceleration response data was provided by NASA Goddard Space Flight Center for a test article that was flown in 1998 on a Black Brant sounding rocket. The measured flight interface acceleration data was used as the reference acceleration spectrum. Using this acceleration spectrum, three analytical methods were used to estimate the force limits. Standard random and force limited vibration tests were performed and the results are compared with the flight data. Implementing the force limiting technique resulted in a reduction in the interface force and response acceleration at the payload natural frequency by over two-orders of magnitude as compared to the standard vibration test. The response acceleration and interface force data from the force limited vibration test still provided a conservative envelope of the flight data over the range force limiting was in effect.

## Introduction

In standard random vibration tests, the payload is mounted to a rigid fixture and driven to a specified acceleration spectral density (ASD). This test approach results in an over test at the payload's fixed-base natural frequencies. Two major factors contribute to this over test problem. The first factor is that the ASD specification is based on a conservative envelope of maximum expected acceleration values based on flight tests with similar payloads/launch vehicles, ground tests, analytical predictions, or a

combination of analytical and empirical methods. Unfortunately, enveloping eliminates notches in the interface acceleration associated with resonant response of the payload. The second factor contributing to the over test problem is the difference in impedance between the rigid test fixture and the flight mounting. Mounting the test article to a three-inch thick aluminum test fixture during a standard vibration test is normal practice at NASA Langley Research Center. When the test article is mounted to the flight vehicle, the payload acts as a vibration absorber at frequencies near its fixed-base natural frequencies.<sup>1</sup> This reduces the interface force and acceleration at these particular frequencies resulting in notches in the flight data. After enveloping, these notches are removed from the test specification. Applying the enveloped ASD to a rigidly mounted payload results in excessive interface forces and response accelerations at the fixed-base natural frequencies of the payload.

The force limited vibration testing technique<sup>1-4</sup> was developed to minimize the over testing associated with enveloping the acceleration spectral density and differences in flight versus test mounting impedance. Force limiting is implemented by dual control testing where both the interface acceleration and force are controlled during the vibration tests. Force limited vibration testing has been established as an accepted practice at NASA.<sup>1,2</sup> NASA Langley Research Center (LaRC) has not used this technique on a flight payload. This paper documents the demonstration of the force limited vibration test technique at NASA LaRC. Validation of the technique was based on flight data<sup>5</sup> provided by NASA Goddard Space Flight Center (GSFC) for a test article that was flown in 1998 on a Black Brant sounding rocket. This paper will describe the force limit prediction methods, test article, test setup, and results for the force limited vibration tests. For this study, the ASD used for all tests and force limit predictions was the actual flight interface acceleration data (not enveloped) provided by GSFC. This reduced the amount of conservatism usually seen in the acceleration specification and allowed for a better assessment of the force limit prediction methods. Comparisons will be made between the force limited vibration test results, standard vibration test results, and the flight data.

## **Force Limit Prediction Methods**

The force limit prediction methods are used to determine the force spectral density needed when conducting force limited vibration tests. Several prediction methods are described in references 1 and 2. For this study, three of the prediction methods were used to define the force limits. The methods used were:

1. Simple Two-Degree-of-Freedom System (Simple TDFS)
2. Complex Two-Degree-of-Freedom System (Complex TDFS)
3. Semi-Empirical (S-E)

A detailed description of the force limit prediction methods is provided in references 1 and 2. In this section, a brief summary of the methods will be provided.

## **Simple TDFS Method**

The Simple TDFS method<sup>1,2</sup> was derived from the TDFS shown in figure 1. The equation used to develop the force limits for this method was:

$$S_{FF} = S_{AA} * M_2^2 * [1 + (\omega/\omega_0)^2 / Q_2^2] / \{ [1 - (\omega/\omega_0)^2]^2 / (\omega/\omega_0)^2 / Q_2^2 \} \quad (1)$$

The frequency ratio can be written in terms of the masses as:

$$(\omega/\omega_0)^2 = 1 + (M_2/M_1)/2 \pm [(M_2/M_1) + (M_2/M_1)^2/4]^{0.5} \quad (2)$$

where,

$S_{FF}$  = Force spectral density

$S_{AA}$  = Acceleration spectral density

$M_1$  = Frequency dependent residual mass for the source

$M_2$  = Frequency dependent residual mass for the load

$Q_2 = 1/(2 * \zeta_2)$  = Quality factor for the load

$\zeta_2$  = Percent critical damping for the load

The interface force limit specification,  $S_{FF}$ , was calculated from the specified interface acceleration spectral density,  $S_{AA}$ , multiplied by a frequency dependent scale factor. Apparent mass measurements were used to estimate the frequency dependent residual mass terms as will be described in a subsequent section. An estimate of the quality factor was also obtained from the apparent mass measurement for the load.

## **Complex TDFS Method**

The Complex TDFS method extends the TDFS model to include both the residual and modal masses of the source and load. The equation used to develop the limits for this method was:

$$S_{FF} = S_{AA} * M_2^2 * F(m_1, M_1, m_2, M_2, Q_1, Q_2) \quad (3)$$

where,

$S_{FF}$  = Force spectral density

$S_{AA}$  = Acceleration spectral density

$F(m_1, M_1, m_2, M_2, Q_1, Q_2)$  = Frequency dependent scalar function

$m_1$  = Frequency dependent modal mass for the source

$M_1$  = Frequency dependent residual mass for the source

$m_2$  = Frequency dependent modal mass for the load

$M_2$  = Frequency dependent residual mass for the load

$Q_1 = 1/(2 * \zeta_1)$  = Quality factor for the source

- $\zeta_1$  = Percent critical damping for the source
- $Q_2 = 1/(2 * \zeta_2)$  = Quality factor for the load
- $\zeta_2$  = Percent critical damping for the load

The interface force limit specification,  $S_{FF}$ , was calculated from the specified interface acceleration spectral density,  $S_{AA}$ , multiplied by a frequency dependent scalar function. A detailed derivation of the scalar function and tables of values are provided in reference 1. In this study, tabulated values<sup>1</sup> were used with an assumed quality factor of 50 for both the source and load. The frequency dependent residual and modal mass terms were estimated from measurements of the source and load apparent mass as will be described in a subsequent section.

### **Semi-Empirical Method**

Similar to the TDFS methods, the Semi-Empirical method calculates the interface force limit specification,  $S_{FF}$ , from the specified interface acceleration spectral density,  $S_{AA}$ , multiplied by a frequency dependent constant. However, for this method, the constant is based on interface force data for similar mounting structures and test items. The equations used to calculate the force limits were:

$$S_{FF} = S_{AA} * M_2^2 * C^2 \quad \text{for } f < f_0 \quad (4a)$$

$$S_{FF} = S_{AA} * M_2^2 * C^2 / (f / f_0)^2 \quad \text{for } f > f_0 \quad (4b)$$

where,

- $S_{FF}$  = Force spectral density
- $S_{AA}$  = Acceleration spectral density
- $C$  = Empirical constant
- $f$  = Frequency
- $f_0$  = First natural frequency
- $M_2$  = Frequency dependent residual mass for the load

The constant C is estimated based on test data for similar hardware configurations. For this study,  $C^2$  was extracted from a graph, which was provided in references 1 and 2, based on the normalized force specification from a Simple Two-Degree-of-Freedom System. A value of  $C^2 = 2.60$  was estimated based on the assumed quality factor of 50 for the load. The exponent of the frequency ratio will also vary dependent on the configuration. For our study, which has a plate in bending, the  $1/f$  roll-off above the first natural frequency was appropriate.

## **Test Article**

The structure that was used to demonstrate the force limiting vibration test technique at LaRC was designed and developed at GSFC.<sup>5</sup> The test article was flown on a Black Brant sounding rocket (Figure 2) in 1998. This sounding rocket is a small multistage rocket, which has sub-orbital flight capabilities with a flight range of 400 to 1200 km. Figure 3 shows the test article mounted to a section of the sounding rocket. A schematic of the test article is shown in figure 4. The test article consists of three 0.125-inch thick aluminum plates. The two outside plates shown in figure 4 are defined as the source plates. Each source plate is attached to the flight vehicle with two bolts. A bar weighing 0.26 lb is attached to each source plate. The central plate, as shown in figure 4, is defined as the load portion of the test article. The load plate is attached to the two source plates at four positions. Force transducers are sandwiched between the attachment points of the load and source plates and used to measure the interface force. Mounted to the center of the load plate is a 0.52 lb bar. In this test configuration, the load plate would represent the payload and the source plates would represent the flight-mounting interface.

For this study, GSFC provided the load portion of the test article and detailed drawings of the assembly. The source plates were fabricated at LaRC based on the drawings.

## **Test Setup**

This section describes the source apparent mass, load apparent mass, and force limited vibration test setups. Two test setups were required. For the source apparent mass measurements, an impact test on the cantilevered source plate was required. The load apparent mass measurements and force-limited vibration tests were conducted with base-drive excitation for the load plate mounted to a shaker.

### **Source Apparent Mass Test Setup**

Before any calculations were performed to determine the force limits, the residual mass for both the load and source plates were acquired from apparent mass measurements. The apparent mass was measured as the frequency response function (FRF) between the force and acceleration. A smooth curve was placed through the apparent mass data to acquire the residual mass. The residual mass for the source and load were then used in the calculation of the force limits from the three prediction methods.

The source apparent mass was measured from an impact test on one of the source plates. Ideally, this measurement would be obtained with the source structure mounted to the flight vehicle. However, this was not possible for this study. Therefore, the cantilevered source plate shown in Figure 5 was used to simulate the source plate mounted to the rocket. Figure 5 also shows the two accelerometers that were mounted at the load attachment points. Drive point frequency response between the

impact force and response acceleration were measured at the load attachment points. Figure 6 shows the magnitude of the drive point frequency response. As mentioned previously, the residual mass for the source plate was obtained by fitting a smooth curve to the data. As shown in Figure 6, the curve is flat to the first natural frequency and then rolls off at  $1/f^2$ . Symmetry was assumed for the two identical source plates, so, the resulting residual source mass was multiplied by two.

### **Load Apparent Mass and Force Limited Vibration Test Setup**

The test setup for the load apparent mass and force limited vibration tests is shown in Figure 7. These tests were performed with the load plate mounted on a Ling model 308V shaker. A close-up photograph of the load plate and instrumentation is shown in Figure 8. The validation data for this study was provided by GSFC from a 1998 flight test.<sup>5</sup> Therefore, it was important to use accelerometers and force transducers that were similar in mass, size, and dynamic range to those used in the flight test. Three PCB model 352M92 accelerometers were used for all vibration tests as shown in figure 8. Two of the accelerometers were mounted on the test fixture to measure the interface acceleration. The third accelerometer was mounted to the center of the load plate to measure the response acceleration. The total interface force was measured using four Kistler model 9251A tri-axial force transducers. These transducers were sandwiched between the load plate and the test fixture. During vibration tests, the four force transducers were summed to obtain the total force.

The manufacturer for the force transducers recommends a preload of 5600 lbs. This results in sufficient contact forces to reliably measure the shear forces ( $F_x$  and  $F_y$ ) and the vertical force ( $F_z$ ). For this study, only the vertical force ( $F_z$ ) was of interest. Unfortunately, the preload was more than a flight bolt could withstand. Therefore, the bolts were preloaded to their recommended manufacture value of 3800 lbs., and a system level calibration was performed on the mounting setup (see Figure 8). At frequencies well below the first natural frequency, the plot of the force over acceleration will become asymptotic to the total mass (or weight when using acceleration in g's) of the system. If the weight of the system has already been measured, then a system level calibration factor can be determined for the force gages.

The load apparent mass, ratio of interface force to interface acceleration, was measured using  $\frac{1}{4}$  g sine sweep over a frequency 10 to 500 hertz. The results are shown in Figure 9 along with the residual mass estimated from this data. The residual mass for the load plate was obtained by fitting a smooth curve to the data to eliminate the resonant peaks. The curve is flat to the first natural frequency and then rolls off at  $1/f$ . As stated previously, the curve should become asymptotic to the total weight of the system at frequencies well below the first natural frequency. The asymptotic value of 1 pound shown in Figure 9 was in good agreement with the measured weight of the system of 0.96 pounds.

To demonstrate the force limited vibration test technique, two base-drive random vibration tests were performed over the frequency range of 20 to 500 Hz. The first was

a standard random vibration test that controlled the interface acceleration. The second was a force-limited vibration test that used dual control of the interface acceleration and interface force.

## **Results and Discussion**

### **Force-Limit Predictions**

The force limits were calculated using equations (1) through (4) and the results are shown in Figure 10. As shown, the force limit predictions from the Simple TDFS, Complex TDFS, and Semi-empirical methods all produced similar results. The Semi-empirical method was the most conservative from 20 to 314 Hertz and the Simple TDFS was the most conservative from 314 to 500 Hertz. An envelope of the three predictions was used to define the force spectral density (FSD) for the force limited vibration tests. A graph of the force spectral density that was used during the force limited vibration tests is also shown in figure 10.

As mentioned previously, the equations for each method require the input acceleration from the flight data. The acceleration used in the calculations was the actual flight data.<sup>5</sup> Since the study was trying to validate the force limited vibration test approach, the flight interface acceleration data was not enveloped. This reduces the conservatism seen in the acceleration spectrum and resulting force limit prediction. However, the reader should note that when an enveloped acceleration spectrum is used the conservatism would also be reflected in the force limit predictions.

### **Force-Limited Vibration Test Results**

The interface accelerations for the flight data, standard vibration test, and force-limited vibration test are shown in figure 11. Since the flight interface acceleration data was used as the input acceleration, the results for the standard vibration test are almost identical to the flight data. However, the results for the force limited vibration test show a notch in the interface acceleration near the first natural frequency of the payload (274.5 Hertz). Near the first natural frequency the interface force has reached the force limit and becomes the limiting control signal. Once past this natural frequency, the force drops off and the acceleration once again becomes the limiting control signal.

Figure 12 shows the corresponding interface forces for the flight data, standard vibration test, and force-limited vibration test. The force limit spectrum is also shown in Figure 12. From the graph, it is apparent that the force limit was reached near the first natural frequency of the payload (274.5 Hertz). Implementation of the force limiting technique resulted in a reduction in the interface force by two-orders of magnitude at the payload natural frequency as compared to the standard vibration test. The interface force data from the force limited vibration test still enveloped the flight data over the range where force limiting was in effect. The flight interface force data exceeds the force data measured in the standard random and force limited vibration test at frequencies

between 70 and 120 Hz. Over this frequency range, the standard and force limited vibration tests are identical. Therefore, the differences were attributed to differences in the flight versus test setup and were not associated with the application of the force limiting technique.

The response acceleration at the center of the load plate is shown in Figure 13. Comparing the standard vibration test data to the flight data, the over testing at the natural frequency of 274.5 Hz is easily seen. However, during the force limited vibration test, the response acceleration is reduced by two orders of magnitude at the test article natural frequency as compared to the standard vibration test. This is consistent with the reductions found for the interface force. The response acceleration for the force limited vibration test envelopes the flight data over the entire 20 to 500 Hz range.

## **Conclusions**

The capability to perform force limited vibration testing was demonstrated in the NASA Langley Research Center Vibration Laboratory. Using measured flight input acceleration data, force limits were estimated based on three analytical methods. An envelope of the three force limit estimates was used in the tests. Application of the force limited vibration test technique resulted in a two-order of magnitude reduction in the response acceleration and interface force that the payload had to endure at the payload natural frequency as compared to the standard vibration test. The response acceleration and interface force data from the force limited vibration test enveloped the flight data over the range where force limiting was in effect. Therefore, the force limited vibration test was still conservative. Force limited vibration testing was demonstrated as a viable technique for reducing the amount of over test at payload natural frequencies.

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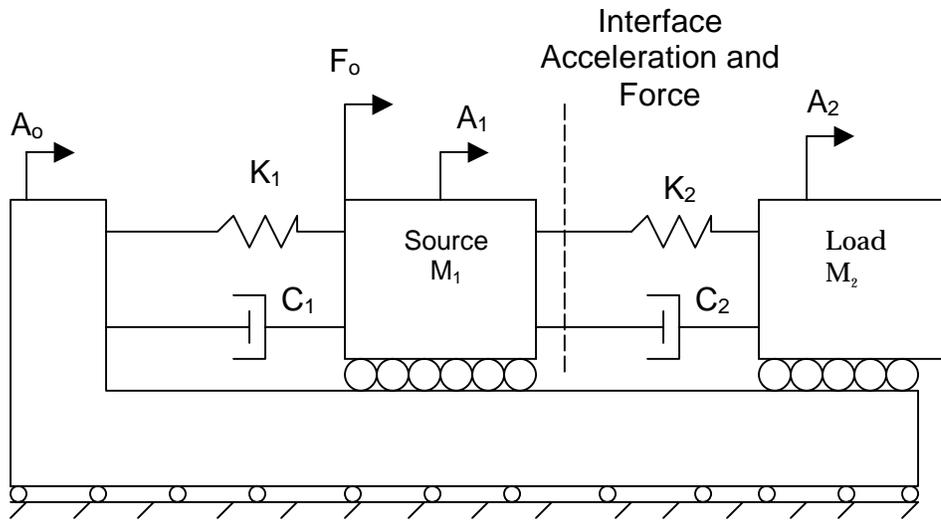


Figure 1. Simple Two-Degree-of-Freedom System model.

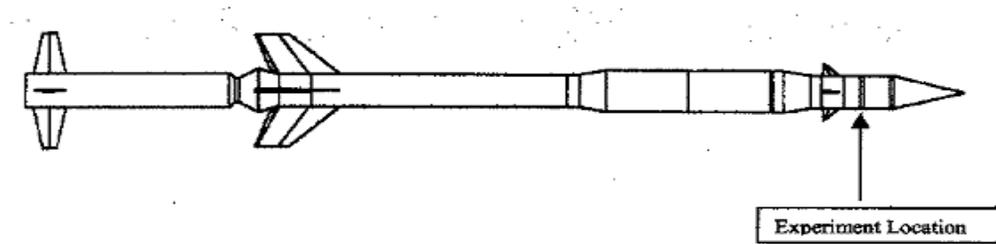


Figure 2. Drawing of the Black Brant sounding rocket showing the experiment location



Figure 3. Test article mounted to a section of the sounding rocket.

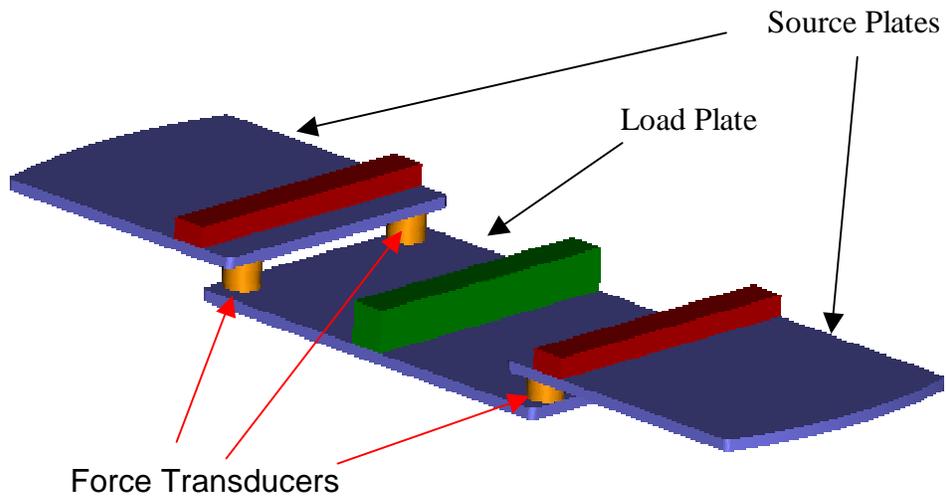


Figure 4. Schematic of the test article flow by NASA GSFC.

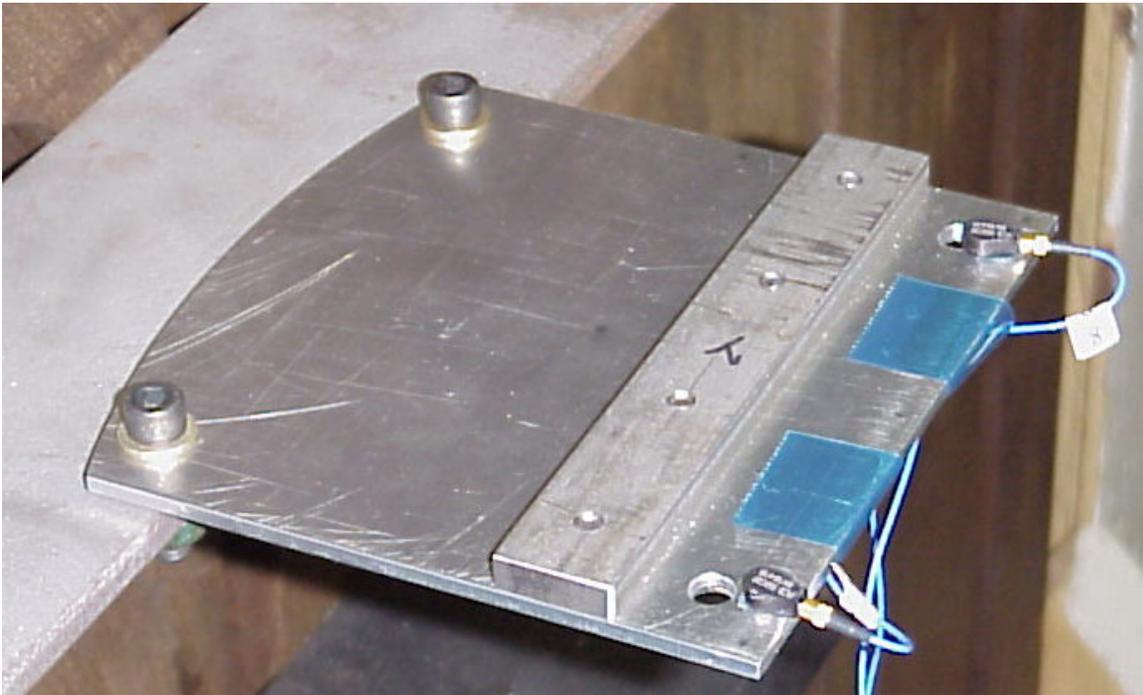


Figure 5. Test setup for the source apparent mass test.

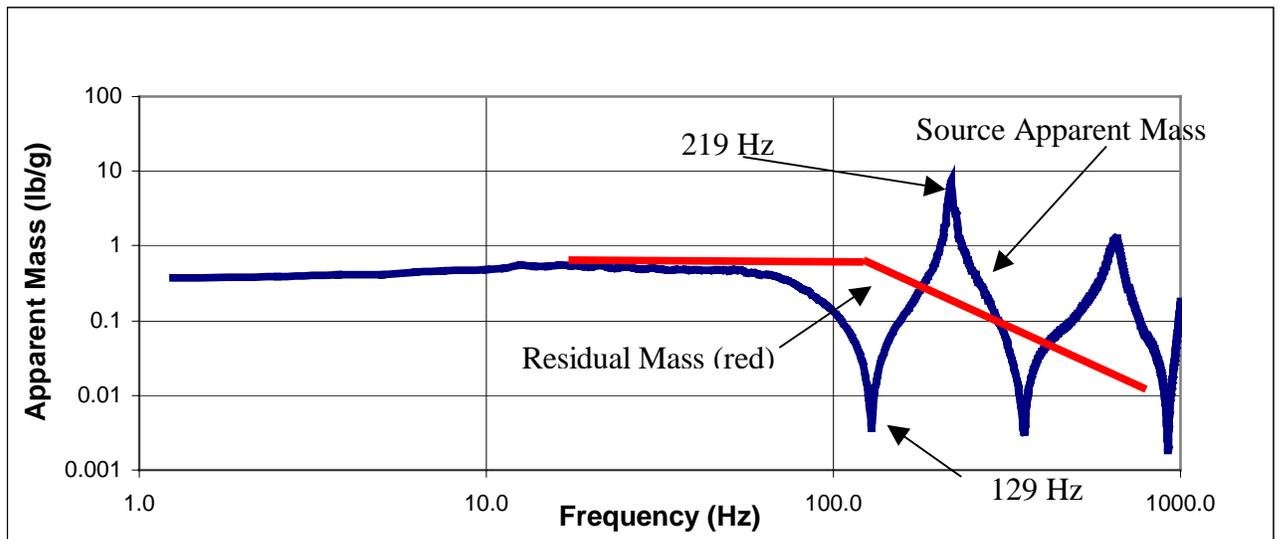


Figure 6. Measured source apparent mass and residual mass curve.

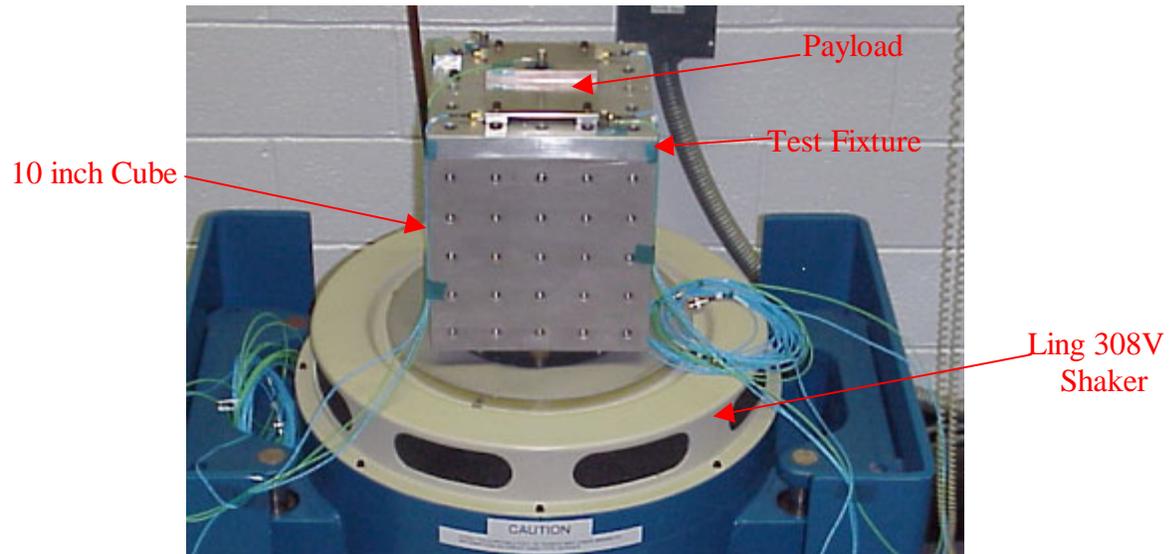


Figure 7. Test setup for the load apparent mass and force limited vibration tests.

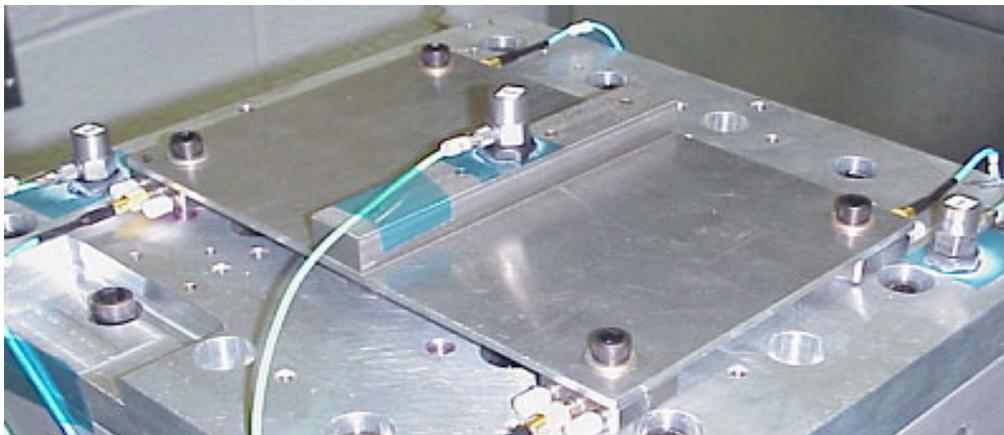


Figure 8. Instrumentation setup for the load apparent mass and force limited vibration tests.

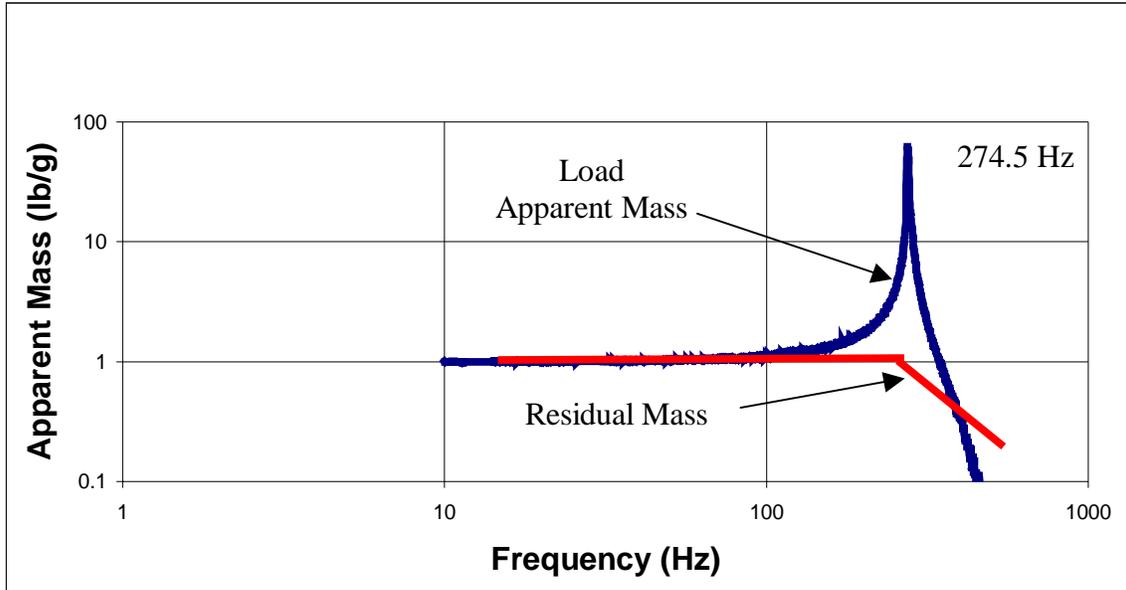


Figure 9. Measured load apparent mass and residual mass curve.

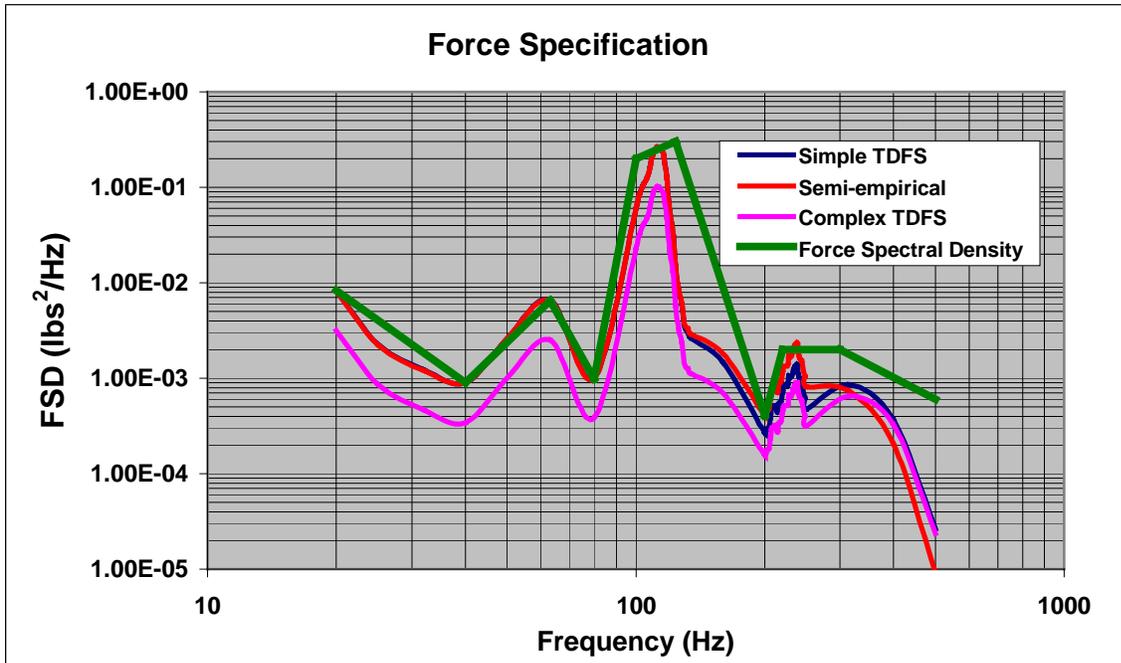


Figure 10. Predicted force limits and resulting enveloped force spectral density.

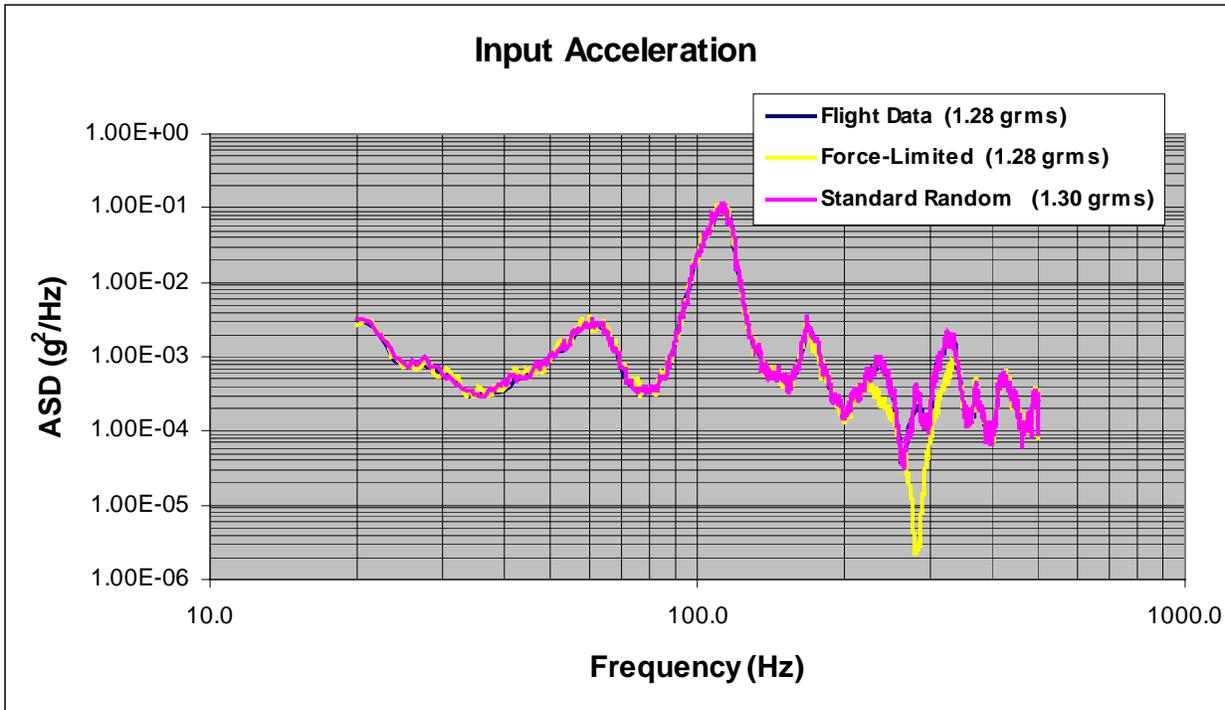


Figure 11. Measured interface acceleration for the flight, standard random vibration, and force limited vibration tests.

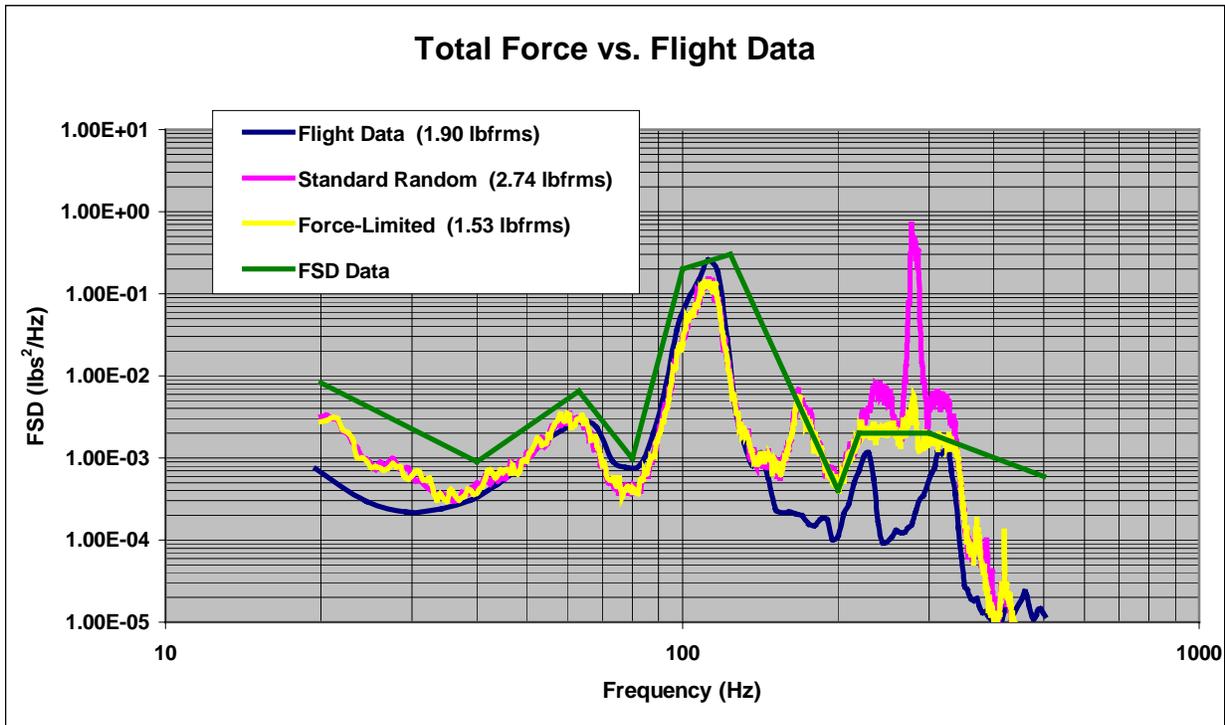


Figure 12. Measured interface force for the flight, standard random vibration, and force limited vibration tests.

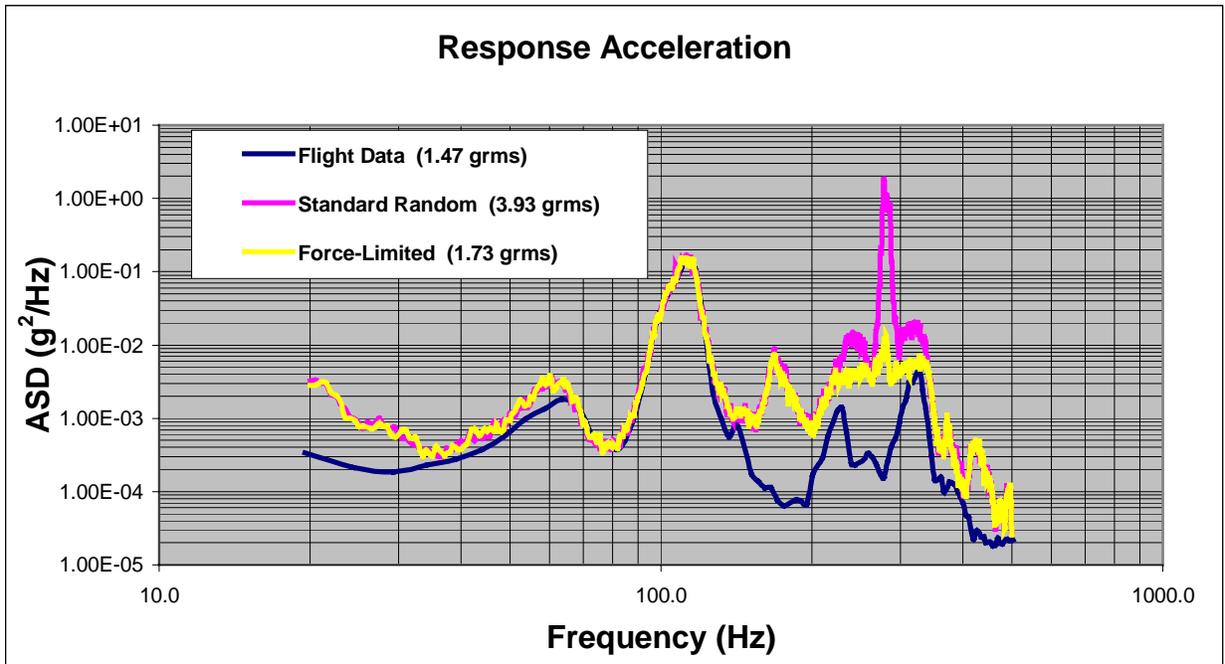


Figure 13. Measured payload response acceleration for the flight, standard random vibration, and force limited vibration tests.

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